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Three-dimensional finite-element analysis of maxillary protraction with and without rapid palatal expansion

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SUMMARY The aims of this study were to determine the reaction of the craniofacial bones on the protraction force transferred to the maxillary body, and whether or not the midpalatal suture had opened during skeletal Class III treatment.

A computerized tomograph was obtained from a dry skull with a normal occlusion to construct a three-dimensional finite-element model (3D·FEM) of the craniofacial bones and the maxillary teeth to simulate actual bone reactions. A protraction force of 500 g was applied at the first premolar region, directed 20 degrees inferior to the occlusal plane. The displacement and the stress distribution of the craniofacial bones and sutures were then calculated using the ANSYS 5.3 program dividing the analysis into two simulations, based on whether or not the midpalatal suture was opened.

The results showed that there was less compressive stress and greater tensile stress in the circumaxillary suture areas when the midpalatal suture was opened. The amount of displacement and deformation when the midpalatal suture was opened also demonstrated a decrease in upward–forward rotation of the maxilla and zygomatic arch and greater amounts of displacement in the frontal, vertical, and lateral directions compared with no opening of the midpalatal suture. Analysis of these results showed that maxillary protraction produce similar changes to normal downward and forward growth of the maxilla and was achieved with accompanying opening of the midpalatal suture.

Introduction

The modalities of a skeletal Class III malocclusion, which is caused by abnormal growth of the jaws or growth disharmony, appear as overdevelopment of the mandible, underdevelopment of the maxilla, or a combination of both. The treatment of choice would be growth modification in the skeletal Class III adolescent patient, and orthodontic camouflage treatment or orthognathic surgery after growth had ceased. There have been several studies using orthopaedic techniques that inhibit growth of the jaws or modify growth direction, to correct the skeletal discrepancies by changing the biological state of the craniofacial sutures and the cartilaginous area. Oppenheim (1944) noted that it was impossible to push backward or reduce the size of the mandible, but found that the maxilla could move forward using extraoral protraction force.

The results of a number of animal experiments have shown that a maxillary protraction appliance, with controlled force, is effective on anterior displacement and bone formation at the cartilaginous suture area of the maxillary complex (Dellinger, 1973; Kambara, 1977; Jackson and Kokich, 1979; Nanda and Hickory, 1984). When the maxilla is protracted, the circumaxillary suture is opened and the bone is filled in that area. Nanda and Hickory (1984) noted, based on the functional matrix theory, that the maxillary growth pattern was similar to the effect of maxillary protraction, and the displacement pattern of the maxillary complex and zygomaticomaxillary suture can be altered by the direction of the traction force. Clinical studies have also shown that treatment of skeletal Class III subjects with maxillary protraction is effective (Irie and Nakamura, 1975; Cozzani, 1981; Turley, 1988; Mermigos *et al.,* 1990; Baik, 1995; Baccetti *et al.*, 1998; Filho *et al.*, 1998; Sung and Baik, 1998).

To predict bony change by orthopaedic force, consideration of the intraoral appliance design and the direction of forward traction are important. Research using a finite-element model (FEM), applied to the displacement of the maxilla, are limited (Kim and Sohn, 1985; Tanne *et al.*, 1989; Miyasaka *et al.*, 1994; Ko and Kim, 1995). However, their investigations differed from reported clinical circumstances, i.e. a tension force was applied on the first molar or canine. No research has been undertaken on the differences in forward traction when used either with or without rapid palatal expansion (RPE), or with or without a united craniofacial bone for three-dimensional (3D) FEM. In this study, therefore, the craniofacial bone was divided and analysed separately, focusing on the maxilla, zygomatic arch, and circumaxillary sutures. The purpose was to analyse the stress distribution and displacement of the maxilla, zygomatic arch, and circumaxillary sutures based on whether the midpalatal suture was opened during maxillary protraction.

Materials and methods

A computerized tomography (CT) was obtained of a dry skull with normal occlusion to construct a 3D FEM of the craniofacial bones and maxillary teeth.

From the occlusal surface of the maxillary teeth to the infraorbital rim, the CT sections were taken at 2 mm intervals, and from the infraorbital rim and above at 3 mm intervals. Each section was reconstructed layer by layer around the standard coordinates to obtain a 3D image. The anatomical structures in the midfacial area were divided into 3D elements by measuring the dry skull (Figure 1a,b). The craniofacial bones were assumed to be composed of spongious and compact bones, and for the properties of each material, Young's modulus (E) and Poisson's V ratio (Table 1) were used as in previous studies (Carter and Hayes, 1977; Cook *et al*., 1982; Orr and Carter, 1985).

The boundary limitation was as follows: the margin of foramen magnum as a fixed point, the upward and downward, forward and backward, and right and left displacement was constrained; the forehead as a fixed point with forward and backward displacement constrained; the shape and load was made symmetric around the X–Y axis (vertical and central section); and the central section was restrained so that there was no right or left displacement (Figure 2).

To separate the midpalatal suture by RPE, a Hyrax-type appliance was designed incorporating the left and right maxillary first premolars and the first molars, which made the maxilla into one unit, and transferred the orthopaedic force effectively to the maxilla through the teeth during protraction.

The RPE appliance opened the suture at a rate of 0.2 mm per turn for 15 days. In the first instance, the screw was turned twice a day until the suture was opened a total of 6 mm. Assuming that the suture was opened 3 mm per side, a displacement force was given at the first premolar and first molar area. The protraction force of 500 g was directed 20 degrees inferior to the occlusal plane (−20 degrees around the Z-axis; Figure 3).

The total number of model elements was 22 236, nodes 71 714, and the degrees of freedom 53 142. The total nodes with boundary limitation were 554 and the total constrained degree of freedom 609. The data were compared in a symmetrical half-model condition (Figure 4).

With the above materials and under such conditions, the displacement and the stress distribution were measured in two simulations, i.e. whether the midpalatal suture was open (simulation B) or not (simulation A). The protraction force was 500 g, and directed 20 degrees inferior to the occlusal plane.

For stress analysis, the principal stress was divided into maximum tensile and maximum compressive stress (kg/mm^2) and the stress distribution on the circumaxillary sutures was compared, i.e. frontomaxillary, nasomaxillary, zygomaticotemporal, and zygomaticomaxillary sutures.

The amount of displacement was measured at anterior nasal spine (ANS), point A, prosthion (Ps), and posterior nasal spine (PNS), which are generally used when comparing the effects of an orthopaedic appliance following maxillary protraction. The amount of displacement (mm) at each point in the X-, Y-, and Z-direction were compared with the amount of 3D displacement using the ANSYS 5.3 program (ANSYS, Canonsburg, Philadelphia, USA; δ, mm; Figure 5).

Results

Comparison of the stress distribution between simulations A and B

When examining the main stress distribution, with regard to maximum tensile stress distribution, there was a wide range of stress from above the apex of the maxillary first premolar and the maxillary first molar to the zygomaticomaxillary suture. The maximum tensile stress appeared to be posterior to the zygomaticotemporal suture at the zygomatic arch in simulation A. For simulation B, these stresses appeared narrower with slightly larger tensile

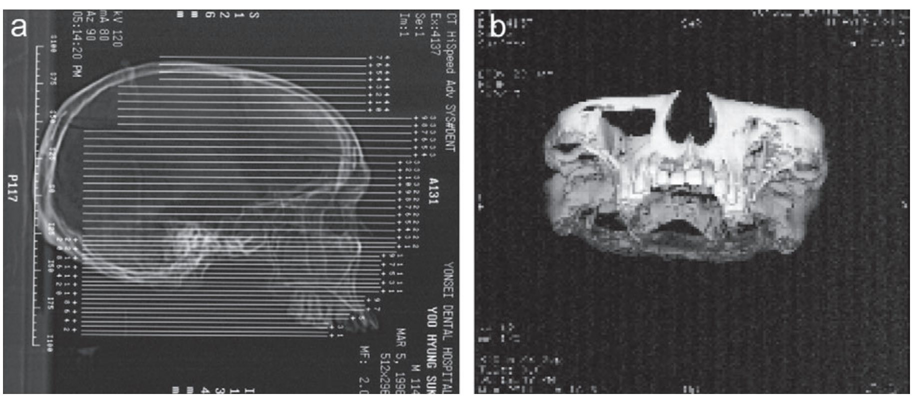

Figure 1 Computerized tomograph of (a) the dry skull and (b) three-dimensional reconstruction of the craniofacial bones.

Table 1 The physical properties of the materials used.

	Young's modulus (kg/mm²)	Poisson's ratio (V)
Cancellous bone	137	0.3
Compact bone	1370	0.3
Suture	0.7	0.4
Teeth	2070	0.3

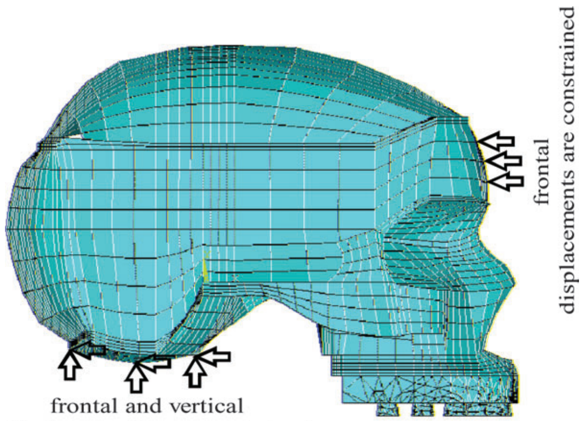

Figure 2 The boundary limitations on the finite-element analysis.

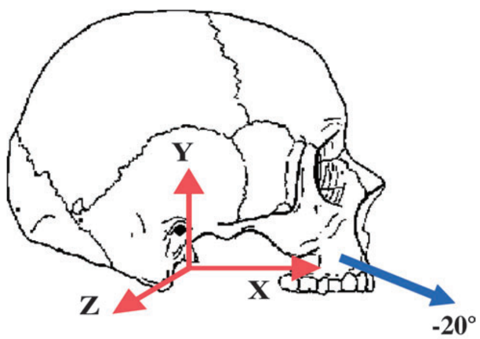

Figure 3 Three-dimensional standard co-ordinates and direction of the maxillary traction.

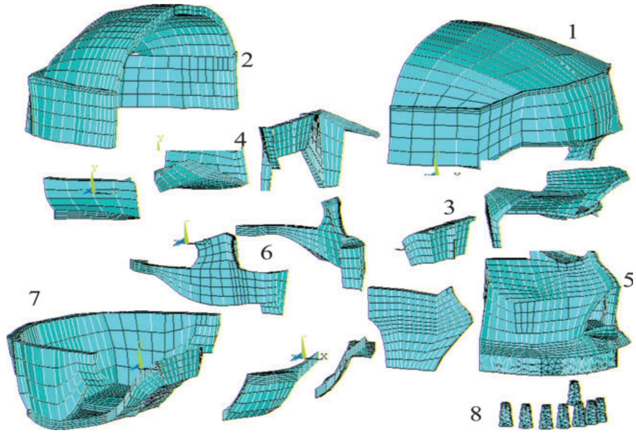

Figure 4 The modelling of the craniofacial bones and their separated bony components: (1) frontal bone, (2) parietal bone, (3) ethmoid bone and vomer, (4) sphenoid bone, (5) maxilla, (6) zygomatic arch, (7) occipital bone, and (8) maxillary teeth.

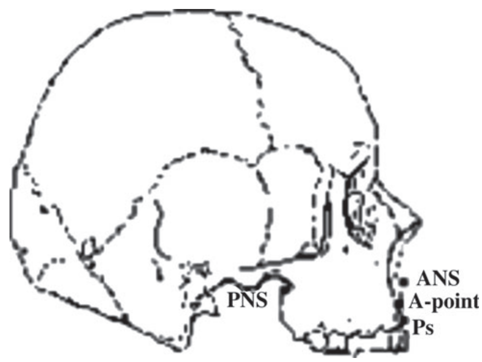

Figure 5 The points used to compare the amount of the displacement: Ps (prosthion)—the most anterior point of the palatal bone at the alveolar process in the median line; ANS—anterior nasal spine; PNS—posterior nasal spine; A point—subspinale.

stresses at the inferior border of the nasal bone to the first premolar and the apex of the palatal root of the first molar in the maxilla compared with simulation A. For the zygomatic arch, larger maximum tensile stresses were observed at the inferior border of the zyomaticomaxillary suture (Figure 6a–h).

With regard to maximum compressive stress distribution, in simulation A there was a weak stress at the frontonasal and nasomaxillary sutures in the maxilla, and at the zygomaticomaxillary and zygomaticotemporal sutures in the zygomatic arch. For simulation B, narrower and slightly larger compressive stress than simulation A occurred at the apex of the maxillary first premolar and in the zygomatic arch. Larger values for maximum compressive stress than in simulation A were observed at the lateral wall of the orbit (Figure 6a–h).

For simulation B, with a separated midpalatal suture, there were smaller compressive stresses and large tensile stresses than with simulation A at the frontomaxillary, nasomaxillary, zygomaticotemporal, and zygomaticomaxillary sutures (Table 2, Figure 7).

Comparison of the amount of displacement between simulations A and B

The amount of the displacement was measured using the datum points of Ps, point A, ANS, and PNS on the *X*-, *Y*-, *Z*-axes, and each was compared separately and their displacement was calculated.

For simulation B, anterior, lateral, and vertical displacement of the maxilla was larger than for simulation A. The antero-superior rotation of the maxilla was less in simulation B than in simulation A (Table 3, Figures 8 and 9a,b).

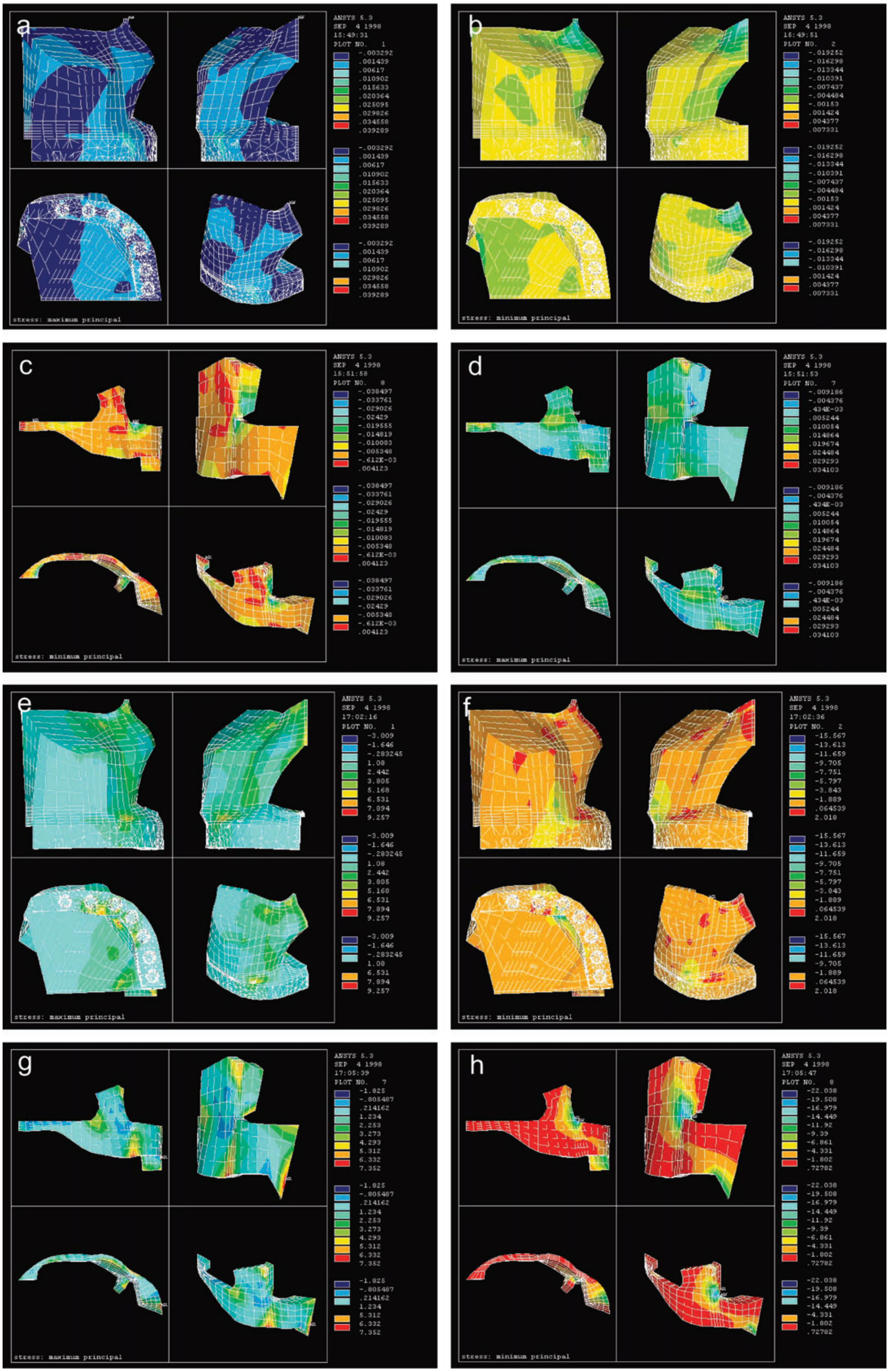

Figure 6 The maximum tensile (left) and compressive (right) stress distributions in simulations A and B for the maxilla (a and b, e and f, respectively) and (c and d, g and h, respectively) for the zygomatic arch. All figures are aligned as follows—upper left: right view (−*Z* direction); upper right: frontal view (−*X* direction); and lower left: occlusal view (+*Y* direction).

Table 2 A comparison on stress distribution between simulation A (midpalatal suture not opened) and B (midpalatal suture opened) at the sutures adjacent to the maxilla (unit: kg/mm²).

	Simulation A		Simulation B	
	Maximum tensile stress	Maximum compressive stress	Maximum tensile stress	Maximum compressive stress
Frontomaxillary suture	+0.001	−0.016	+3.805	None
Nasomaxillary suture	None	−0.013	+3.805	None
Zygomaticomaxillary suture	+0.010	−0.001	+7.352	−1.802
Zygomaticotemporal suture	+0.014	−0.005	+0.214	None

+, tensile stress; −, compressive stress.

Table 3 Comparison of the amount of displacement of simulations A and B at the sutures adjacent to the maxilla (unit: mm).

	Simulation A				Simulation B			
	X	*Y*	*Z*	δ (Net)	*X*	*Y*	*Z*	δ (Net)
Ps	0.008	0.005	0.001	0.009	3.132	–0.388	3.657	4.830
A	0.006	0.005	0.001	0.007	3.132	–0.388	3.657	4.830
ANS	0.005	0.005	–0.001	0.007	2.814	–0.388	3.249	4.315
PNS	0.005	–0.001	–0.001	0.005	2.496	–1.168	0.800	2.869

Ps, prosthion; A, point; ANS, anterior nasal spine; PNS, posterior nasal spin.
X, antero-posterior displacement (+, anteriorly; −, posteriorly). *Y*, vertical displacement (+, superiorly; −, inferiorly). *Z*, lateral displacement (+, lateral; −, median).
$\delta(\text{NET}) = \sqrt{X^2 + Y^2 + Z^2}$.

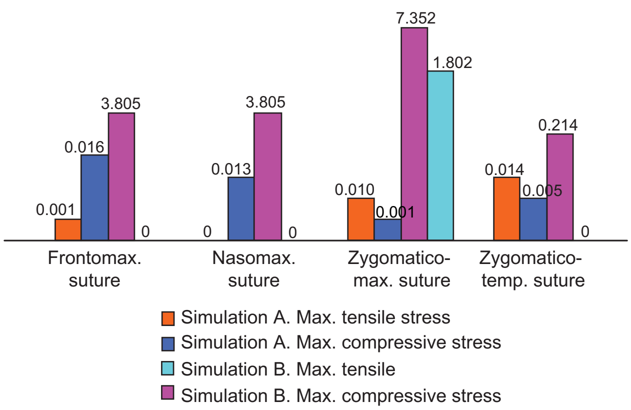

Figure 7 Comparison of the stress distribution between simulations A and B at the sutures adjacent to the maxilla.

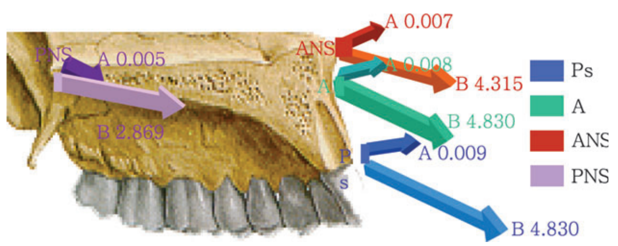

Figure 8 Comparison of the amount of displacement between simulation A and B.

Discussion

Skeletal Class III malocclusions appear in various conditions and patterns. There are many controversies concerning the treatment modalities and treatment timing of skeletal Class III malocclusions with respect to skeletal and dental discrepancy, age, and residual growth. A reduction in growth of the maxilla is caused not only by the antero-posterior divergence but also by a transverse variation, resulting, in many cases, in posterior crossbites. Haas (1961) reported on the orthopaedic effect of RPE, which produced a forward and downward tipping of the maxilla with concomitant downward and backward mandibular rotation. These orthopaedic changes facilitated the correction of a mild Class III malocclusion. RPE is effective for correction of transverse discrepancies and also for protraction of the maxilla by remodelling the nine circumaxillary sutures. Turley (1988) stated that palatal expansion 'disarticulates' the maxilla and initiates cellular responses in these circumaxillary sutures, allowing a more positive reaction to protraction forces. Melsen (1975) confirmed these increased cellular responses to RPE.

Many of the sutures affected by protraction headgear are also affected by RPE. Among them, the zygomatic

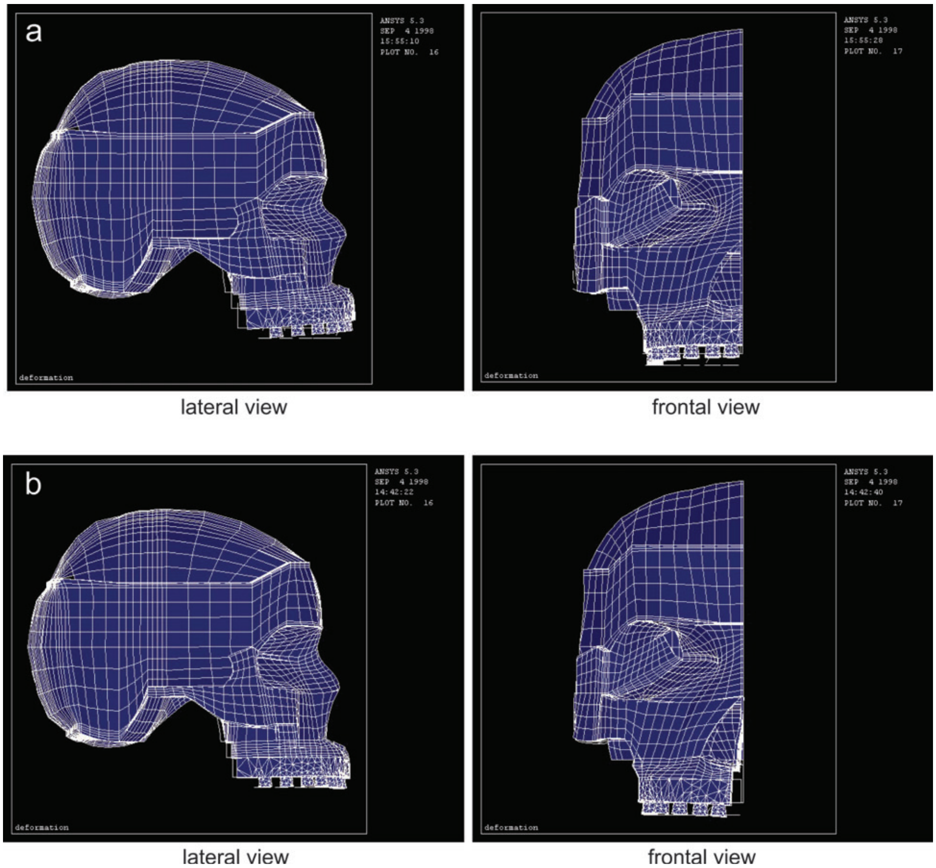

Figure 9 Deformation of (a) simulation A and (b) simulation B.

buttress, especially the zygomaticomaxillary suture, has been shown to have a major resistance to forces generated by both RPE and protraction (Tanne *et al*., 1989; Tanne and Sakuda, 1991). Likewise, in this study, there was less compressive and greater tensile stress to the adjacent suture area of the maxilla and zygomatic arch when the midpalatal suture was opened. The zygomaticomaxillary suture in particular was shown to have the highest stress concentration.

Because the direction of maxillary protraction force affects the transformation of the craniofacial complex, the direction of force application during protraction is important. Itoh and Chaconas (1985), who used a photoelastic method to compare the effect of a protraction force directed parallel and 20 degrees inferior to the occlusal plane and passing through the maxillary first premolar, found there was minimal antero-superior rotation of the maxilla. Hata *et al*. (1987), Kang and Ryu (1988), and Lee and Ryu (1992) used a strain gauge method or laser holography and reported the same results.

For minimal rotation of the maxilla during protraction, when the force is applied inferior to the occlusal plane, the effective point of force application has been reported to be at the lateral incisors (Canut and Dalmases, 1990), the canines (Nakano and Miura, 1980; Ngan *et al*., 1997), the first premolar (Proffit, 1992; Ko and Kim, 1995), and the first molars (Tanne *et al*., 1989). In clinical research using cephalometric analysis, the displacement of ANS and point A in the group protracted with a separated midpalatal suture was found to be larger than in the group where a labiolingual appliance and protraction device was used (Baik, 1995; Ngan *et al*., 1997; Baccetti *et al*., 1998; Filho *et al*., 1998; Saadia and Torres, 2000).

In the present study, a protraction force angled 20 degrees inferior to the occlusal plane was applied through the first premolar. Comparison of the amount of displacement and deformation, dependent on whether the midpalatal suture was opened or not, showed there was a decrease in the upward–forward rotation of the maxilla and zygomatic arch. There was also a greater amount of displacement in all frontal, vertical, and lateral directions, when the midpalatal suture was opened, compared to when there was no opening of the midpalatal suture.

The differences in this investigation compared with previous finite-element analysis studies are that it was possible to observe the stresses not only on the body of the maxilla and the zygomatic arch but also on the zygomaticomaxillary, zygomaticotemporal, nasomaxillary, and frontomaxillary sutures separately. The modelling was undertaken by separating the maxilla from the craniofacial bone through the circumaxillary sutures.

Kragt *et al*. (1982), in a hologram study, reported that when orthopaedic force was applied to a dry skull the initial reaction was similar to the reaction of the skull *in vivo*. Nakagawa and Ichikawa (1986), using a strain gauge method, found no difference in the pattern of stress distribution between a child's skull and an adult's skull. With the present 3D FEM, the craniofacial bone was assumed to be an isotropic material and the properties of each material were used in previous study, so even though there are anatomical and histological differences in craniofacial bones and the midpalatal suture between a growing child and an adult, there seems little difference in the stress distribution pattern and the amount of displacement in these simulations.

However, the physical changes due to age in the internal structure of bones and sutures and the successive changes of the physiomechanical data and the chin (which is the support for the protraction force) should be included in the modelling, for an accurate, whole structural reproduction of the cranial bones. As the effects on facial musculature and other soft tissues also need to be investigated, more progressive research with clinical identification of dynamic modelling is required.

Conclusion

To clarify the effect of midpalatal suture opening and the displacement and stress of the craniofacial bones following maxillary protraction for the treatment of skeletal Class III malocclusions, a 3D FEM was made to reassemble the craniofacial bone at the sutures. When a protraction force of 500 g was applied 20 degrees inferior to the occlusal plane passing through the first premolar with RPE, the amount of displacement and stress at the maxilla, zygomatic arch, and circumaxillary sutures were compared based on whether the midpalatal suture was open or not and analysed. The results were as follows:

1. There was less compressive and greater tensile stress to the circumaxillary suture area of the maxilla and zygomatic arch when the midpalatal suture was opened. The greatest stress was found in the area of the zygomaticomaxillary suture.

2. There was a decrease in the upward–forward rotation of the maxilla and zygomatic arch and also a greater amount of displacement in all frontal, vertical, and lateral directions, when the midpalatal suture was opened, compared to when there was no opening of the midpalatal suture.

3. When the midpalatal suture was opened, the frontal and lateral displacement increased gradually from the upper to the lower part and from the posterior to the anterior part of the maxilla, parallel to the zygomaticomaxillary suture line.

4. Opening the midpalatal suture using a RPE appliance and directing the protraction force inferiorly from the occlusal plane, passing through the maxillary centre of resistance and also through the apical portion of the first premolar, maxillary protraction that is similar to normal downward and forward growth of the maxilla can be effectively achieved.

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